NASA TT F-9513

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N65-32879 (ACCESSION NUMBER) (THRU) 1

22 (PAGES) (CODE)

(NASA CR OR TMX OR AD NUMBER) 31 (CATEGORY)

FACILITY FORM

Translation of "Lagestabilisierung von Satelliten mit der Reaktionsschwungkugel".
Unpubl. MS; Paper presented at the Annual Meeting of the WGLR/DGRR(Wissenschaftliche Gesellschaft für Luft-und Raumfahrt/Deutsche Gesellschaft für Raketentechnik und Raumfahrtforschung), Berlin, September 14-18, 1964.

GPO PRICE $ ______

CSFTI PRICE(S) $ ______

Hard copy (HC) $2.00

Microfiche (MF) .50

ff 653 July 65

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON JULY 1965

NASA TT F-9513

ATTITUDE STABILIZATION OF SATELLITES BY MEANS OF THE FREE REACTION SPHERE

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Discussion of problems arising in the application of the free reaction sphere as a control element in the attitude stabilization of a satellite. Specifically examined are: the selection of the type of bearing for the sphere, the determination of the rotor dimensions, the selection of a propulsion system capable of applying torques to a rotor about any axis, and the measurement of rpm. An experimental device proposed for use in a satellite is described and illustrated.

author

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1. Introduction */1

The problems, occurring in connection with the attitude control and stabilization of satellites, are mainly governed by the environmental conditions prevailing in near-earth cosmic space. These premises, which differ enormously from those prevailing on the surface of the earth or in atmospheric space, including weightlessness, absence of any friction damping, intense high-energy radiation, and absolute vacuum, are the determining design parameters. These are supplemented by the conditions of blastoff under usually very high accelerations and the required life of the satellite which is of the order of magnitude of years, at complete freedom from servicing or maintenance. On the other hand, these extreme conditions also justify attempts to use unorthodox means and

* Numbers in the margin indicate pagination in the original foreign text.

sophisticated technologies, whose application would not be considered under less strict conditions. It may be of advantage in this connection to make use of physical principles which, under terrestrial conditions, are inapplicable or difficult to use.

In this report, the concept "attitude stabilization" is to include the following problem scopes: Primarily, the term is to mean retention of a definite space-fixed orientation of the axes of a space vehicle and compensation of any perturbation-induced deviations from this ideal attitude. Consequently, the control factors of the corresponding control circuits are constants. A generalization is obtained by having the control factors, in part or in totality, follow a program as it occurs in aligning one axis with a fixed point in finity or in singular pendulum motions.

Here, we will refrain from discussing the orbital control, the instrument errors, or the overall control circuit of the stabilization. These topics had been covered in detail elsewhere. We are interested primarily in an investigation of the vanes and control elements required for stabilization and, among these, in the special case of the so-called reaction flyball ("free reaction sphere"), with its application possibilities and problems.

2.1 Review of Various Control Elements /2

As sources for the control elements, required for attitude stabilization, several possibilities are in question, which can be principally subdivided into two groups:

a) utilization of built-up torsion discharge into the external medium;

b) storage of torque at the interior.

A similar subdivision can be made for the perturbation factors, namely,

a) perturbation moments due to interaction with the environment;

b) perturbation moments originating at the interior.

Here it is only a question of viewpoint to decide whether the moments occurring at variable control factors of the rotation of the coordinate system should be added to this control factor itself or to the perturbation factors. Another characteristic differentiation of the perturbation factors, listed individually in the Table, is their curve as a function of time. In this respect, in analogy with the terminology of celestial mechanics, secular and periodic perturbations can be differentiated, which make widely differing requirements on the control elements with respect to optimum selection of the system itself. Secular moments undergo cumulative integration in time, and the only possibility for compensation is the dissipation of angular momentum toward the outside. Conversely, the time integral of periodic moments vanishes, and the method of using internal torque storage may lead to considerable savings in weight and bulk of the required equipment, if long operating periods are involved. Similarly, in the case of statistically distributed perturbation moments, time averaging may yield the same advantages, although certain limits are set by the degree of variance.

The feasible possibilities for the generation of erecting moments are assembled in Table 2. This compilation was made in view of its use in a system with active or passive stabilization. The recent increase in attempts to obtain inherent stability of space vehicles by a skilled utilization of certain perturbation moments for the compensation of other moments, where such stability would then require at most an artificial damping, are disregarded here. So far as can be judged today, it will be impossible to get along without active control elements, in view of the high requirements made on the accuracy and the

TABLE 1: SOURCES OF PERTURBATION MOMENTS

a) Earth's magnetic field, with perturbations by solar activity, in interaction with internal magnetic dipoles

b) Gravitation fields of the earth and other celestial bodies

c) Radiation pressure

d) Meteorite impacts

e) Aerodynamic resistance of the residual atmosphere, asymmetric

f) Moving internal parts

g) Eccentricity of the thrust vector of an orbital propulsion system

h) Rotation of the coordinate system (can be added to the control factor)

i) Electrostatic field

k) Electromagnetic proper radiation.

TABLE 2: ACTIVE CONTROL ELEMENTS

a) Cold-gas jets, using nitrogen or argon

b) Hot-gas jets

c) Vapor-pressure jets

d) Plasma discharge

e) Ion engines

f) Inherent twist or torque

g) Reaction gyros

h) Flywheel

i) Fluid flywheel

k) Flyball (reaction sphere).

In all nozzle aggregates, a differentiation is required between proportional and pulsed thrust control.

frequency response of a given stabilization system.

2.2 Application Fields and Selection /4

The applicability and efficiency of the various control elements depends primarily on the nature of the perturbation moments which must be compensated and modulated. Secular perturbation moments require in any case the production of torsion by expulsion of mass or by field coupling. Conversely, torque-storage methods represent an optimum for the modulation of purely periodic moments. Rotating masses such as flywheels or flyballs act as a type of sink for angular momentum, with a saturation value given by the mechanical critical values (angular velocity and rotational mass). In this manner, the law of the conservation of moment of momentum can be utilized, which is not possible in the expulsion of mass. Naturally, the question as to which type of stabilization to use is greatly dependent on the mission of the given satellite. For example, in short-lived satellites, less emphasis is placed on the integration effect and weight savings will be obtained by using gas-jet stabilization. Conversely, all satellites with a long life can be optimally designed by extensive utilization of the integration effect. It is of importance here to balance the cooperation of torque production and torque storage in such a manner as to reduce the weight and power requirements of the entire system to a minimum.

Another important criterion for the selection of the control elements is the maximum erecting moment required by the control as well as the necessary resolution limit (threshold value) of the moment. A high maximum moment and a fine resolution are difficult to realize, if at all, for the case of mass expulsion. This requires the use of multistage systems (coarse - fine) and an excessively high consumption of reaction elements (in the case of gas jets) or power (in the case of electric systems which, however, are still in a preliminary development stage). Reaction gyros, at satisfactory resolution, may yield very high erecting moments, but require allowance for couplings over a computer or elimination of such couplings by mounting the unit into an inertia frame or on gimbals. Weight advantages can be obtained only at high rpm which, however, greatly limits the life.

The use of flywheels (solid or liquid) offers all advantages of torque storage but has the secondary effect, undesirable for fine control, of a gyro coupling which is dependent on the corresponding storage state and whose compensation greatly complicates the control system or the required data-handling /5
machines. In addition, frictional moments are generated in the bearings, limiting the resolution of the erecting moment, affecting the life because of bearing wear, and increasing the power consumption.

These disadvantages are avoided when using a free reaction sphere or flyball, although at the price of a relatively complex bearing. This bearing is the main problem which produces the greatest difficulties but, if an optimal solution is found, also offers the most widespread application possibilities.

3. The Free Reaction Sphere and its Problems

The problems in the conception of a flyball as the control element for satellite stabilization can be classified into the following groups:

a) Type of bearing

b) Storage capacity for angular momentum

c) Torque resolution and maximum torque

d) Cross coupling in the three-dimensional drive

e) Vectorial rpm measurement

f) Mechanical stability

g) Testing possibilities before blastoff

h) Reliability.

Naturally, close correlations exist between these individual problem groups, and solutions in one field will always influence all other problems.

4. Bearing Systems

For the bearing of the reaction sphere, a number of systems had been suggested by various interested parties; these are compiled in Fig.1, together with a relative evaluation from various viewpoints.

This evaluation is based on data by Bendix Systems, modified on the basis of our own investigations, and does not claim absolute validity. According /6 to this evaluation, there might be some superiority (possibly somewhat exaggerated) of the electrostatic suspension. The individual bearing systems will be discussed in more detail below, according to their principle and applicability.

4.1 Gas Bearing

Types of gas bearings, including static and dynamic variants, have been thoroughly investigated in recent times and applied in widely differing fields, specifically in gyro technology. The dynamic gas bearing whose load-carrying forces are produced by means of rotation, has the obvious drawback that the rotational speed of the supported flyball must never drop below a certain minimum, since the sphere otherwise would make contact with the walls. This results in a dead zone, within which no continuous control is possible. Although the probability for occurrence of such an event is relatively slight, only a highly complex logic, together with a system which is able to dissipate torsion toward the outside, can prevent failure due to this cause. Another undesirable effect is the low stability of a dynamic gas bearing under conditions of weightlessness, which would place an upper limit on the rotational speed.

The conditions are more favorable for static gas bearings. The lower rpm limit is eliminated here and also the upper limits are no longer quite as critical since the clearances, compared to the dynamic bearing, can be made larger. Friction and elastic deformation of the sphere will limit the rotational speed to about 2000 rpm and thus also will limit the storage capacity. Figure 2 gives a schematic view of the design of such a static gas bearing. From theoretical considerations, the following formulas can be derived for the buoyancy and the gas consumption:

$$W = \frac{\pi}{2} P_1 \frac{R^2 - R_0^2}{\ln R/R_0}$$

$$Q = \frac{\pi}{6} \frac{P_1}{\mu} \frac{h_0^3}{\ln R/R_0}$$

Here, 17

W = buoyancy

P_1 = feed pressure

R = outside radius of the bearing

R_0 = inside radius of the bearing

Q = gas consumption

μ = viscosity

h_0 = clearance.

Accordingly, a sphere of a diameter of about 22 cm and a weight of approximately 3.5 kp at 0.01 g acceleration of gravity and a feed pressure of about 1 torr can be kept in suspension. The total gas consumption – computed for air - would be about 20 kg per year. The difficulties lie in the limited life of a system operating with gas in the vacuum of space, since the vacuumtightness or the replacement of gas lost by leakage cannot be guaranteed over long periods of time with the required reliability. However, the technique has been thoroughly tested, and the weight data seem to speak in favor of such a system. From an overall viewpoint, however, the gas bearing cannot be considered the ideal solution. In any case, it must be remembered that, for testing before takeoff, static air bearings could be used as a sort of auxiliary bearing. This would eliminate most of the difficulties occurring in long-time operation.

4.2 Fluid Bearing

The bearing using a lubricant is mentioned here only for completeness. Such bearings are out of question for satellites because of excessive friction, susceptibility to radiative corrosion, and temperature dependence.

4.3 Magnetic Bearing /8

Quite a number of experimental data are available on the suspension of magnetic objects in a magnetic field, which also show the possibility of this type of suspension under acceleration of gravity. The requirements for the bearing of a free reaction sphere differ in various aspects from these tests. Usually, a relatively large air gap was used in these experiments, which would be unfavorable in our case because of the additional requirement of a drive with maximum efficiency (here, 0.3 mm). In addition, the accelerations are no longer restricted to one axis but become three-dimensional. Finally, the amount of acceleration is very small (of the order of magnitude of 0.01 g).

The ponderomagnetic force exerted on a ferromagnetic substance in a magnetic field is given by the expression

$$F = 2A \left(\frac{nI}{d}\right)^2 \cdot \frac{10^{-8}}{0.981} \quad [\mathrm{kp}]$$

Here,

F = force

A = area of the air gap

d = length of the total air gap

n = number of turns

I = current.

Accordingly, in a gravitational field of 0.01 g, slightly more than 6 kp can be kept suspended at 10,000 turns and a current of 20 ma. By nature, the magnetic bearing is unstable to $1/d^2$ because of the proportionality; if d increases because of a minor perturbation, the magnetic force will also increase which, in turn, reduces the distance, and so on. To keep the spacing constant, a control circuit is required which will furnish an artificial stability. Figure 3 shows the block diagram of the overall circuit. The attitude deviation, defined by a sensitive attitude indicator, influences the forces exerted on the sphere, over the suspension characteristic as well as over an "electronic" current control and field-strength control of the magnetic coil. After deducting the inertia forces and after integration, the variation in spacing will /9
be obtained.

In addition to the extremely sensitive stabilization, the main drawback of a magnetic suspension is the coupling of the magnetic moments with the drive motor. The moments result in transverse forces so that the axis of the drive moment no longer coincides with the motor axis. This necessitates a comp. allowance of this cross coupling for the satellite stabilization circuit, which renders the entire system unreliable.

4.4 Electrostatic Bearing

Basically, the loads that electrostatic fields are able to support are much lower than in all other methods discussed above. Therefore, this type of bearing is in question only at greatly reduced acceleration of gravity. In that case, however, this type of bearing has several advantages that may be of decisive influence, specifically in long-time missions. As in the magnetic force, the electrostatic force exerted on a conducting body is proportional to the square of the field strength and thus inversely proportional to the square of the interelectrode spacing. This force can be expressed by the relation

$$F = A \cdot \left(\frac{V}{d}\right)^2 \cdot 4.513 \times 10^{-13}$$

where

F = load-carrying capacity (kp)

A = electrode area

V = applied potential

d = clearance.

By use of a special technique, it is possible to obtain attitude stability in this case. The process operates with alternating voltage generated in a resonance circuit. The space between electrodes and sphere constitutes the capacitance of the oscillating circuit. The principal wiring diagram of the circuit is shown in Fig.4. This results in a force exerted on the sphere, as a function of the clearance, as plotted in Fig.5. When operating on the left flank of this resonance curve, a basically stable suspension is obtained; however, damping of this suspension by suitable electronic means is required so as /10 to prevent oscillations. The required and obtainable supporting forces are plotted in Fig.6 against the radius of solid and hollow steel spheres.

5. Rotor

The main viewpoint in dimensioning the rotor is the obtainable ratio of its mass or of the ratio of the bearing to the supporting weight and the rotary mass, on which the torque storage capacity depends. The main parameters are diameter, material, and wall thickness, since it always will be necessary to work with a hollow sphere. In addition, the diameter also defines the obtainable torque. It must be taken into consideration here that the geometric configuration of the sphere, the equilibration, and the resistance to elastic deformation produced during the rotation must be controllable.

The selection of the rotor material is defined mainly by three requirements. Primarily, mechanical stability must be maintained during rotation. In addition, it is necessary that the torsion required for storage can be absorbed, meaning that the limits of the load-carrying capacity of the suspension must be taken into consideration. In Fig.6, the occurring bearing loads are plotted for solid and hollow steel spheres as a function of the radius, giving also the limit obtainable with an electrostatic suspension.

Finally, the rotor material must be suitable for transfer of the drive moment from the stator, at adequate efficiency and required torque - rpm characteristic. Because of satisfactory machinability and resistance to deformation, the only materials in question are steel and aluminum.

The characteristics decisive for the sizing are mass, rotational mass, and torsion which can be represented by the following formulas, applicable to a /11 hollow sphere:

$$M = \frac{4\pi}{3} \rho r_1^3 \left[1 - \left(1 - \frac{d}{r_1}\right)^3\right]$$

$$I = \frac{8\pi}{15} \rho r_1^5 \left[1 - \left(1 - \frac{d}{r_1}\right)^5\right]$$

$$D = \frac{4\pi^2}{225} \rho r_1^5 \left[1 - \left(1 - \frac{d}{r_1}\right)^5\right]$$

Here,

M = mass of the hollow sphere

ρ = density of the material

r_1 = outside diameter

d = wall thickness

I = rotational mass

n = rpm

D = torsion.

In Fig.7, the deformation of solid and hollow steel spheres is plotted for various diameters, as a function of the rpm.

6. Drive Motor

The drive system must permit the application of torque to the rotor about any axis. For this, three separate stator windings must be arranged in three mutually perpendicular planes. The vectorial addition of the moments produced by the individual stator windings yields the resultant total moment, in amount and direction. The following conditions characterize the drive system:

a) efficiency, i.e., torque by input power

b) curve of torque versus rpm

c) minimum spatial coupling.

The condition a) is self-evident. The torque characteristic, for reasons of optimum usefulness in the control circuit of the stabilization, should not /12 depend too greatly on the rpm; if necessary, greater efficiency must be sacrificed to obtain this result.

Spatial coupling is an effect which occurs specifically only in three-dimensional motors. This effect manifests itself in that the rotating electromagnetic drive field tends to produce a torque not only about the rotational axis but also about an axis normal to this, in the event that a rotational velocity of the rotor about this latter axis is already present.

This drive coupling would have to be allowed for by the control circuit, as is the case in gyro coupling for flywheel systems, which latter are not used here. By proper design and sizing of the stators it is possible to keep them small and constant so that their consideration, if at all required, is quite simple. The individual stator windings are indicated in Fig.9, which gives a sketch of the overall design of a free reaction sphere.

7. Rpm Measurement

For discharging the torque stored in the sphere toward the outside, as soon as saturation by integration of secular perturbation moments is reached, the point at which this saturated state and thus the maximum permissible rpm occur must be determinable. For this, it is required to measure the angular velocity of the spherical rotor, in amount and direction. In practical use, the relative rpm must be individually measured in three mutually perpendicular axes. For example, these test data can be used to obtain the commands for operating the gas jets. In addition, the data obtained during turn-and-bank maneuvers, after integration, will furnish quite accurate data on the executed rotational angle which, then, need only a minor correction by the sensors.

For this rpm measurement, several methods are available, of which only the most important will be listed below:

a) Unbalance effects

b) Optical scanning

c) Reaction on the motor

d) AC tachometer.

The unbalance effects are produced by the tendency of the bearing to /13 retain the geometric center of the sphere. If the center of gravity does not coincide with this, the forces in the suspension are forced to execute oscillations with a frequency which is a direct measure for the rotational speed of the sphere. By decreasing this frequency on all three axes, the desired angular-velocity measurement becomes possible. Although this method appears quite simple, it does require a highly complex computational evaluation of the direct test data, so that its use becomes quite illusory. This applies even more to the optical scanning of some pattern applied to the sphere. Conversely, the reaction of the rpm on the stator of the drive can be used without excessively complicated computations. Since the rpm, however, is measurable only with the motor connected, the data must be stored over the periods without drive. The preferable method seems to use an AC tachometer. Here, the motor windings serve simultaneously as exciter and pickoff windings; in addition, the components of the angular velocity according to amount and sign can be obtained directly across a phase-sensitive rectifier, as direct-voltage data. Figure 8 shows the diagram of such a measurement. Here, the exciter voltage can be kept without difficulty to such a small value that no noticeable reaction, in the form of a torque, is exerted on the rotor.

8. Summary

Figure 9 gives a general sketch of an experimental unit, as it could be used in a satellite. Of course, the design data must be adapted to the particular mission. The design shown here is based on the assumption that it can be used in a satellite for an orbit of approximately 500 km height; this satellite would sight a point on the earth's surface during the fly-over and, during its revolution, align the solar cells with the sun for charging and, finally, store the resultant secular perturbation moments over a sufficiently long period of time so as to prevent excessively frequent torque dissipation. This will yield design data as they are given in Table 3. Let the satellite have a rotational

TABLE 3

DATA OF A PROJECTED FREE REACTION SPHERE

Sphere dimensions:	diameter, 29 cm wall thickness, 0.23 cm
Material of the sphere rotor:	steel
Weight of the rotor:	4.5 kp
Rotational mass of the rotor:	6.7 kg-cm^2
Maximum deformation:	0.008 cm
Maximum rotational speed:	10,000 rpm
Maximum torque:	0.1 m-kp
Torque storage capacity:	0.7×10^9 gm-cm-sec^{-1}
Field strength, at suspension below 1 g:	3×10^5 v/cm
Clearance:	0.25 μ

mass of 4500 kg-m^2 about the axis of its prescribed rotation. Let the total mean perturbation moment be about 200 dyne-cm. Using a free reaction sphere /14 with the given data, it will then be possible to rotate the satellite through 180° in about 110 sec, while the torque accumulated from the perturbation moment must be discharged after about 40 days. Despite the fact that this represents a highly specialized application, the indicated data demonstrate the usefulness of a free reaction sphere for stabilizing a low-flying satellite. However, beyond the available experimental data a considerable amount of further development work will be required before such devices are fully operational. Nevertheless, the expected advantages for the overall system of a satellite equipped with such devices seems to justify further efforts in this direction.

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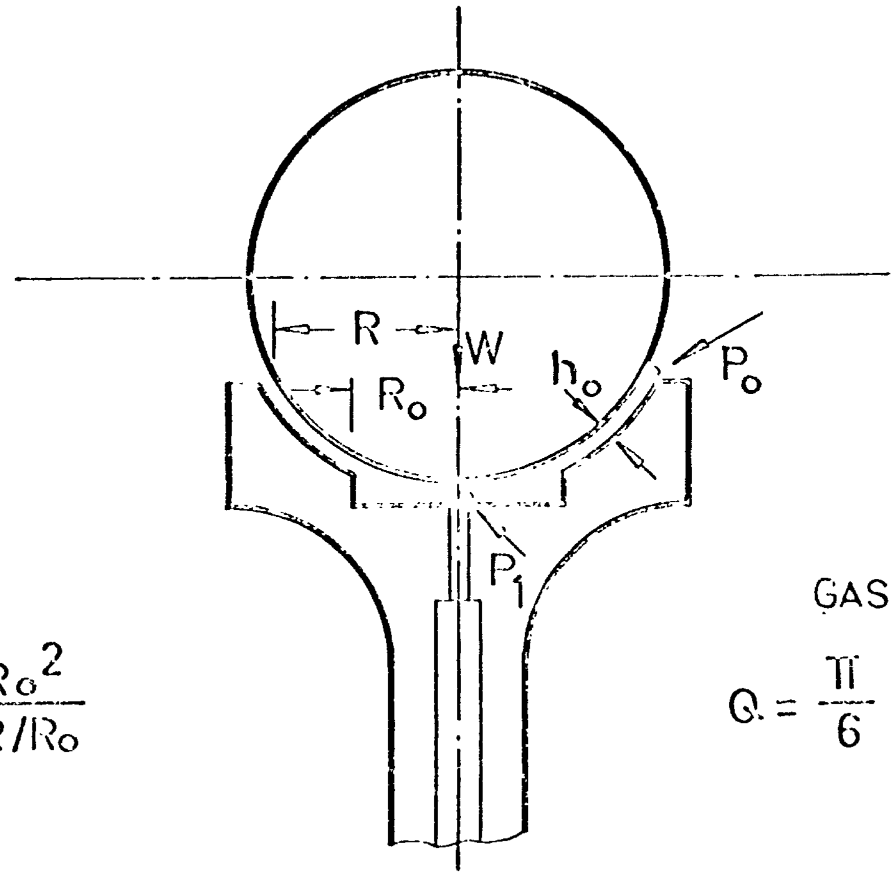
Bearing Type	Braking Moment	Power Consumption	Weight	Mechanical Tolerances	Dimensions	Development Stage	Life
Electrostatic	1	2	2	1	1	3	1
Gas (closed)	3	2	2	2	3	2	2
Gas (open)	3	1	3	2	1	1	3
Gas (dynamic)	3	1	1	5	1	4	2
Fluid	4	4	3	2	3	3	2
Magnetic (repulsion)	2	5	4	1	2	3	1
Magnetic (attraction)	5	5	4	1	1	3	[illegible]

Fig.1 Comparison of Various Bearing Systems



BUOYANCY

$$W = \frac{\pi}{2} P_1 \frac{R^2 - R_o^2}{\ln R/R_o}$$

GAS CONSUMPTION

$$Q = \frac{\pi}{6} \cdot \frac{P_1}{\mu} \frac{h_o^3}{\ln R/R_o}$$

Fig.2 Gas Bearing

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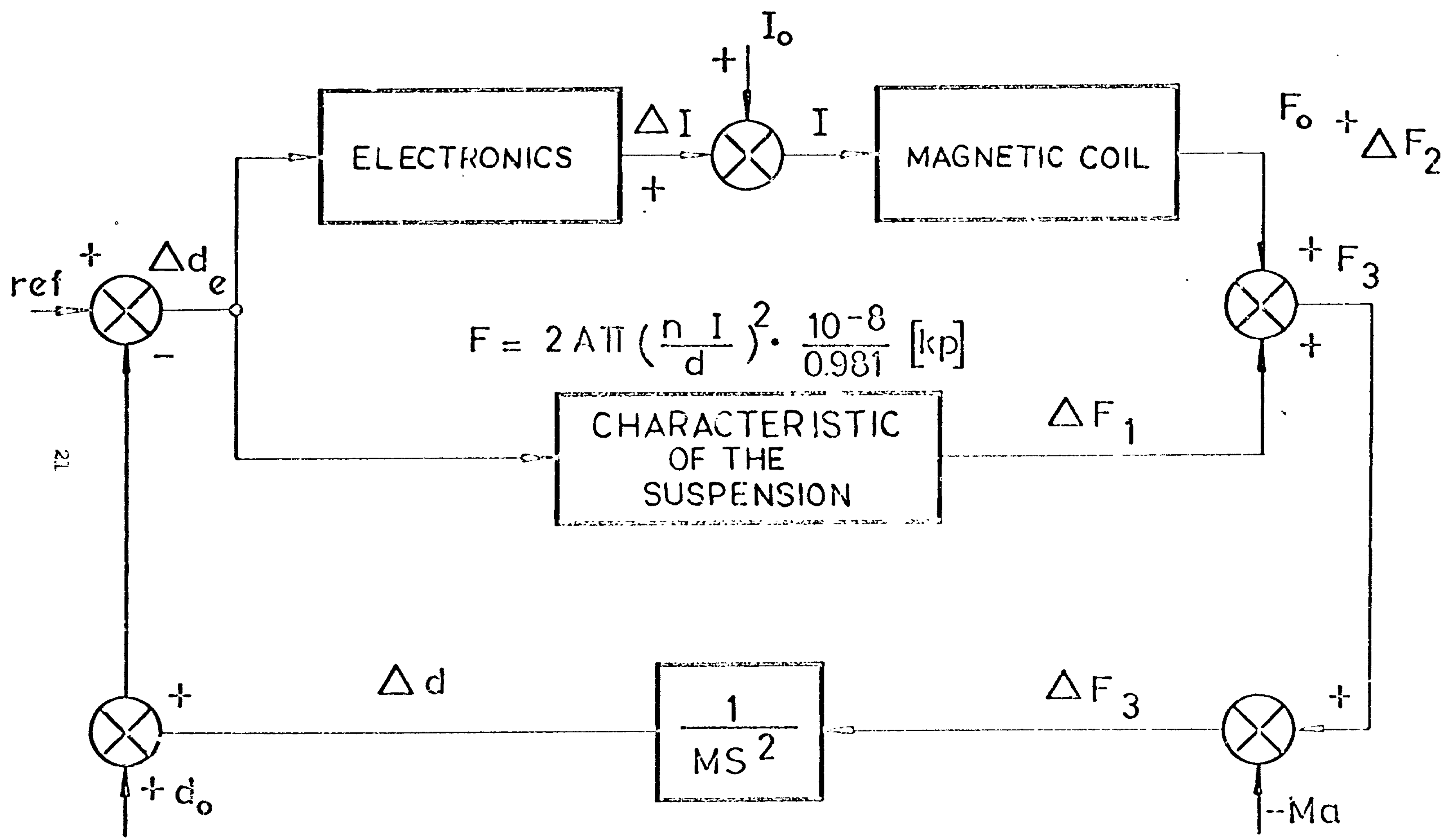

Fig.3 Block Diagram of the Magnetic Bearing

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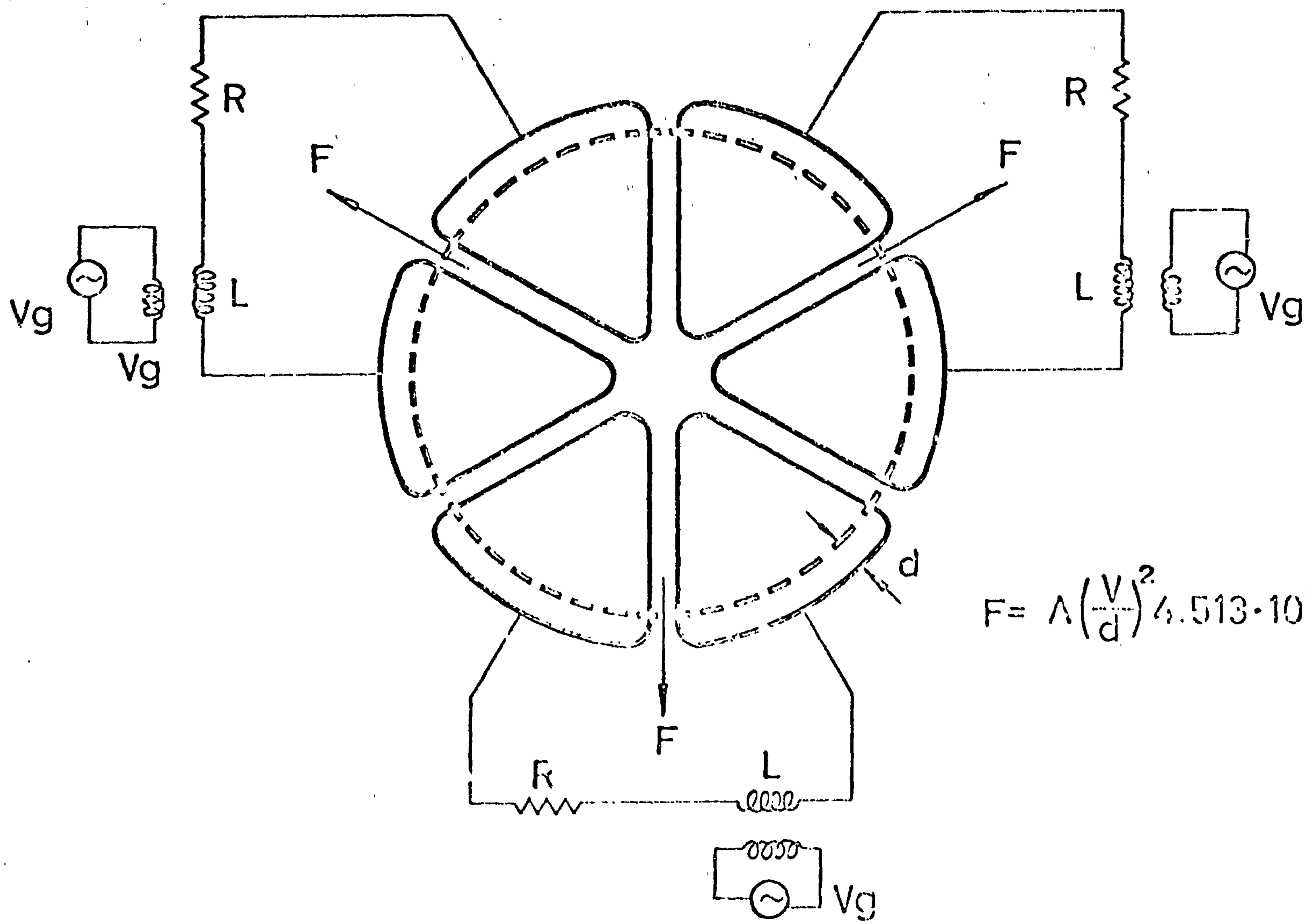
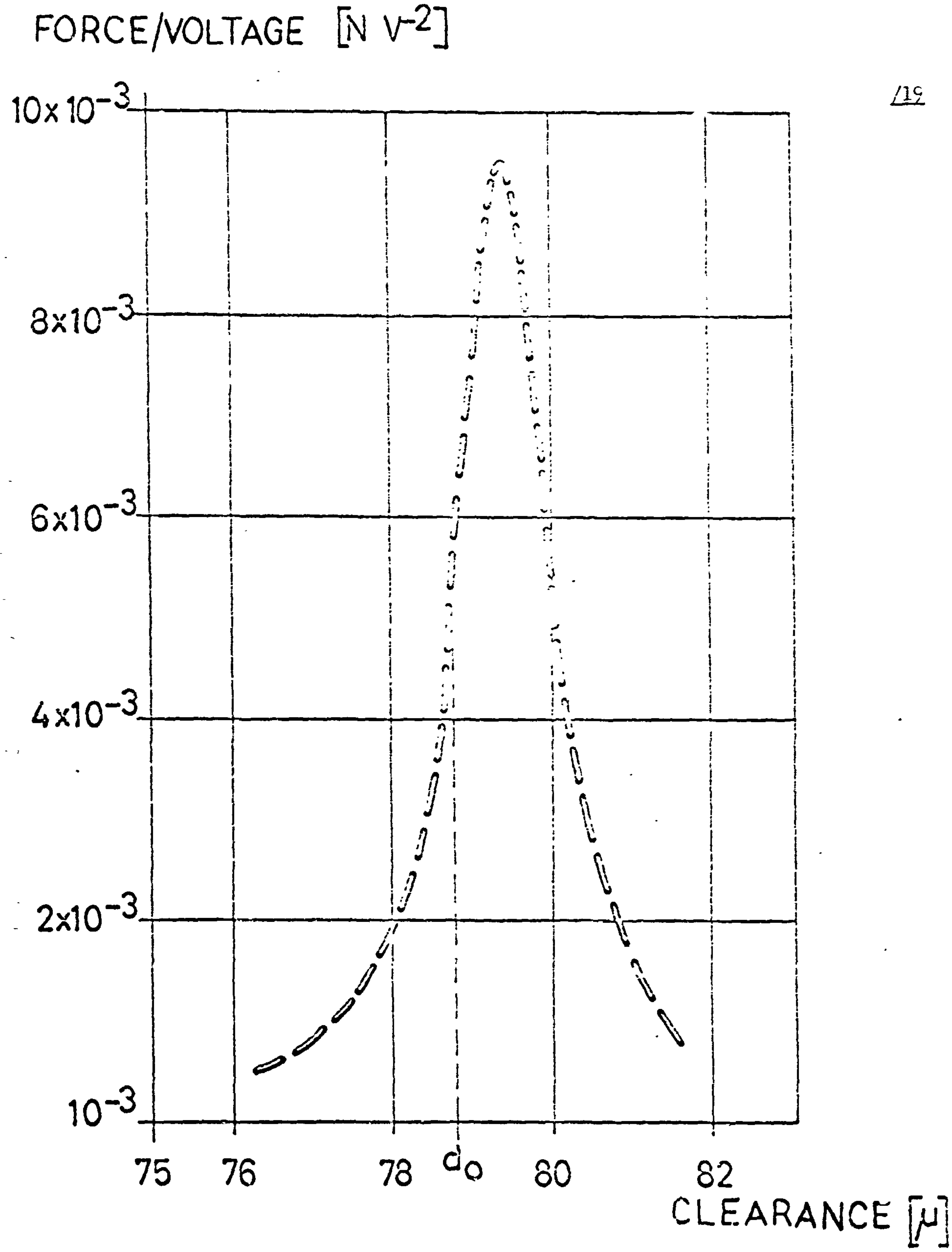


$$F = \Lambda \left(\frac{V}{d}\right)^2 4.513 \cdot 10^{-13} \; [kp]$$

Fig.4 Principle of the S-Bearing

/18


FORCE/VOLTAGE [N V-2]
10x10-3
8x10-3
6x10-3
4x10-3
2x10-3
10-3
75
76
78
do
80
82
CLEARANCE [μ]

/20

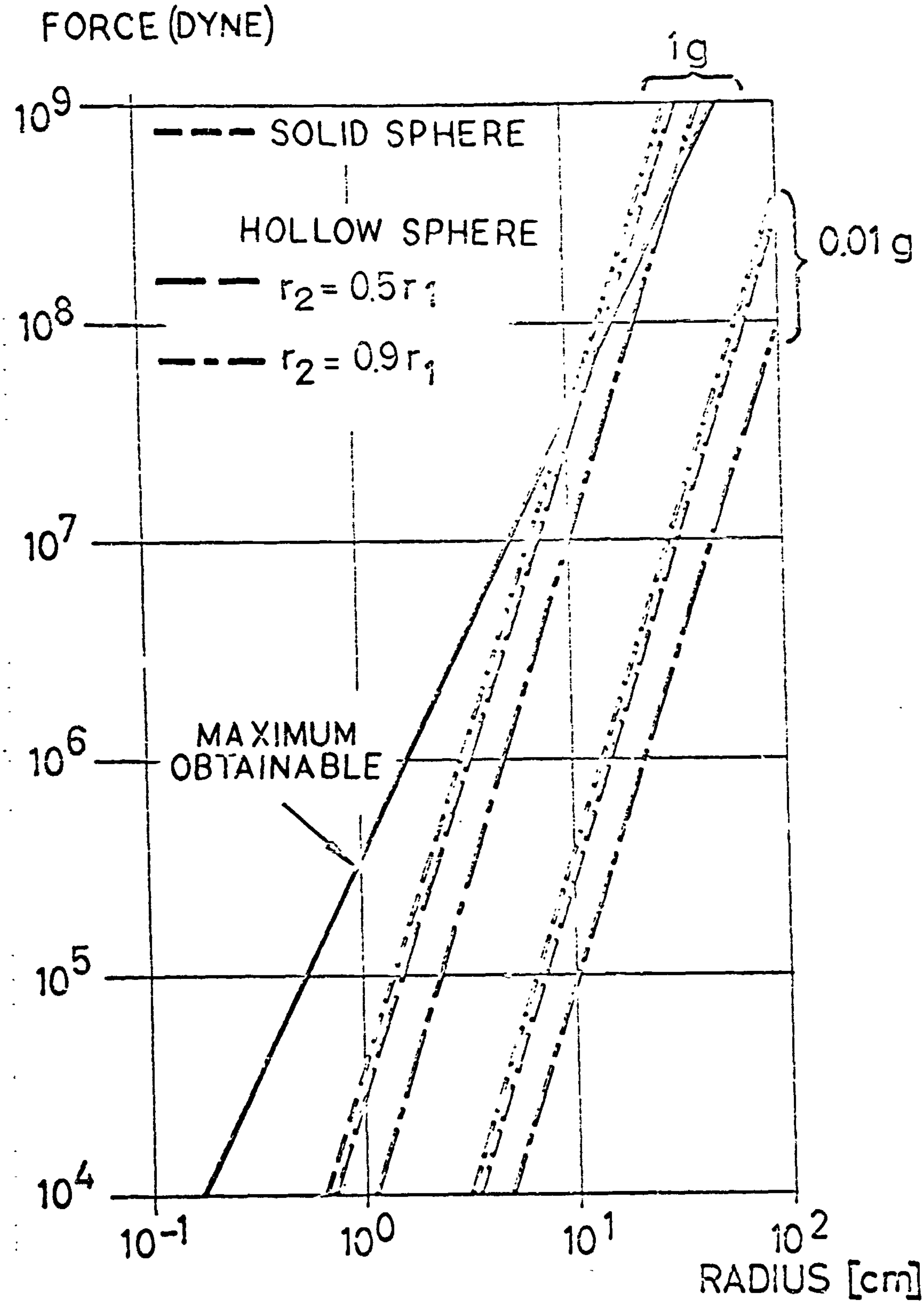


Fig.6 Bearing Loads as a Function of the Sphere Radius

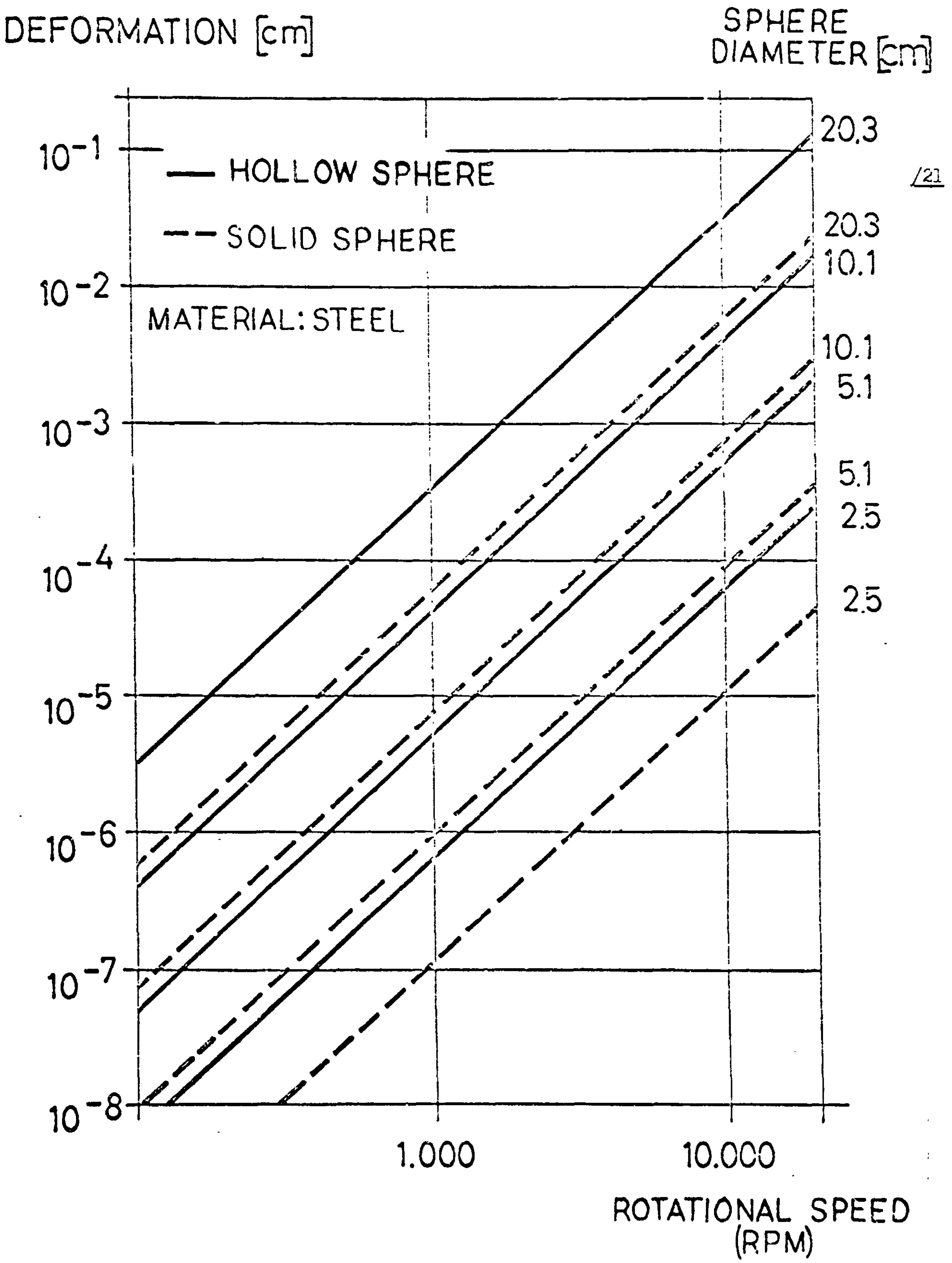


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Fig.7 Deformation

/22

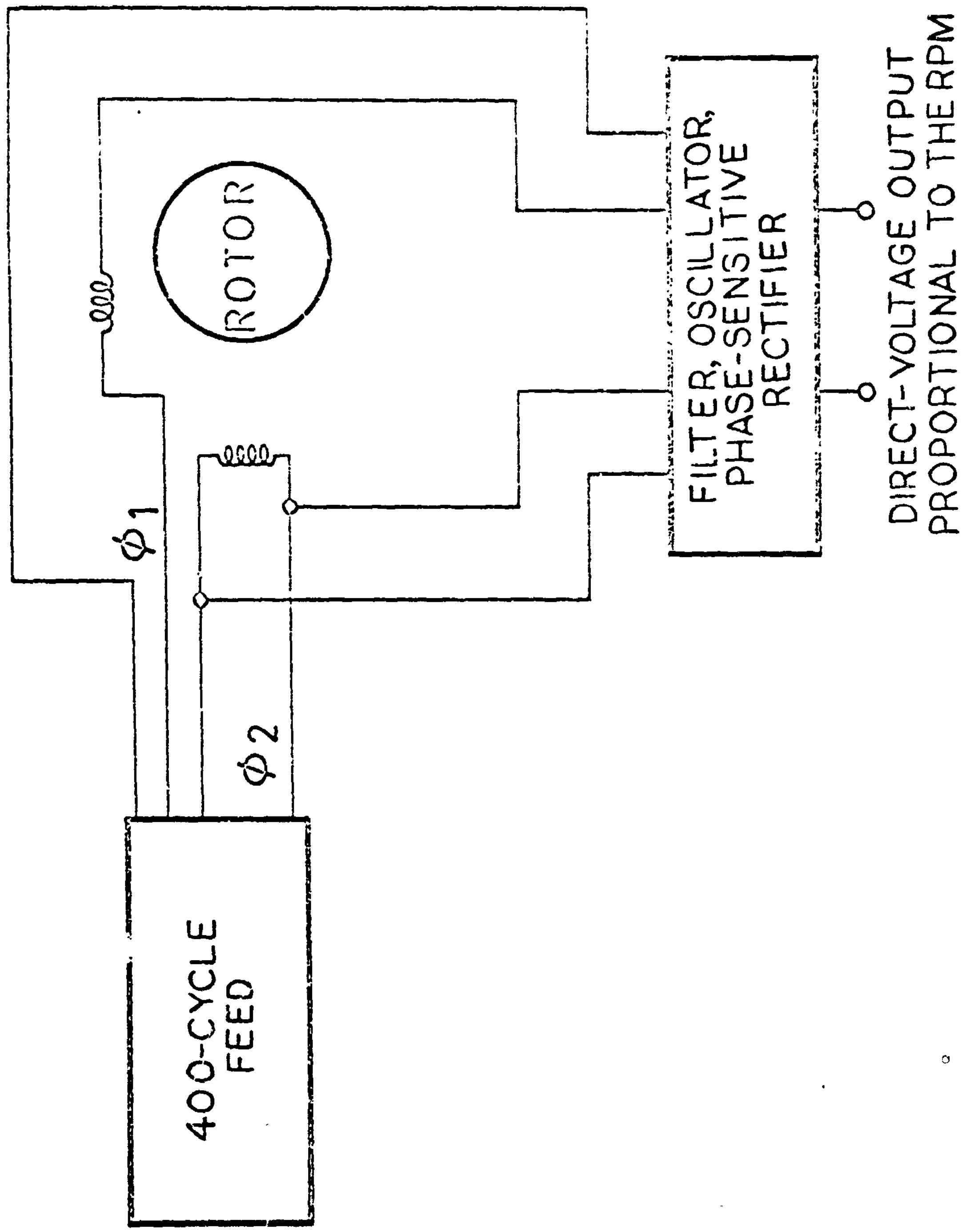

Fig.8 Rpm Measurement